



"Many Options With One Hat"

Welcomes You  
to the

# KDHE Geology and Well Technology Fall Seminar 2015



# **FORMATION PRESSURE FALL-OFF TEST**

also known as Pressure Transient Test

Presented by:

- Wayne Jenkinson, Professional Geologist, T&C
- Dan Murta, General Manager of Consulting, T&C
- Craig Pangburn, Professional Geologist, T&C

# CLASSIFICATION OF WELLS

**Class I disposal well** = Disposal Wells are used to inject hazardous and/or nonhazardous industrial and municipal fluids beneath the lowermost formation containing a source of fresh or usable water. These wells are regulated by the Kansas Department of Health and Environment (KDHE).

Kansas allows only “gravity” injection and does not allow injection under pressure. This reduces the stress on well components, prevents undesirable pressure buildup in the disposal zone and significantly limits the potential for induced seismic activity. Gravity injection allows only the amount of fluid that the formation can naturally accept. There are approximately 50 active Class I wells in Kansas.

**Class II disposal well** = Disposal Wells are used to inject fluids associated with the production of oil and natural gas or fluids/compounds used for enhanced hydrocarbon recovery. These wells normally inject below the lower-most fresh or usable water bearing zone, and are regulated by the Kansas Corporation Commission (KCC). In 2013, there were 16,600 permitted Class II wells in Kansas.

# WHAT IS A PRESSURE FALL-OFF TEST

- A **Pressure Fall-Off** test consists of fluid injected into a well at a constant rate for a period of time, followed by shut-in of the well and monitoring the pressure decline. The pressure change is analyzed using pressure transient analysis, a technique based on the mathematical relationships between flow rate, pressure and time. The information from these analyses helps determine injection potential and skin. It can also derive permeability, reservoir boundary shape and distance and reservoir pressures.

## PLANNING

- The radial flow portion of the test is the basis for all pressure transient calculations. Therefore the injectivity and fall-off portions of the test should be designed not only to reach radial flow, but to sustain a time frame sufficient for analysis of the radial flow period.

## GENERAL OPERATIONAL CONCERNS

- Successful well testing involves the consideration of many factors, most of which are within the operator's control. Some consideration in the planning of the test include:
  - ❖ Adequate storage for the water should be ensured for the duration of the test.
  - ❖ Offset wells completed in the same formation as the test well should be shut-in, or at a minimum, provisions should be made to maintain a constant injection rate prior to and during the test.

# WHAT IS A PRESSURE FALL-OFF TEST

## continued

- Install a full-open valve on the well prior to starting the test so the well does not have to be shut-in to install a pressure recording device.
- The location of the flowline valve on the well should be at or near the wellhead.
- The condition of the well, junk in the hole, wellbore fill or the degree of the wellbore damage (as measured by the skin) may impact the length of time the well must be shut-in for a valid falloff test. This is especially critical for wells completed in relatively low transmissibility reservoirs or wells that have large skin factors.
- Cleaning out the well and acidizing may reduce the wellbore storage period and therefore the after-flow test time of the well.
- Accurate recordkeeping of injection rates is critical including a mechanism to synchronize time reported for injection rate and pressure data.

## WELL TESTING AND THE IDEAL RESERVOIR MODEL

- A well test, in its simplest form, consists of disturbing the reservoir by injecting into a well at a controlled flow rate for a period of time and measuring the pressure response when the well is shut-in.

# WHAT IS A PRESSURE FALL-OFF TEST

## continued

### THE “IDEAL” RESERVOIR MODEL

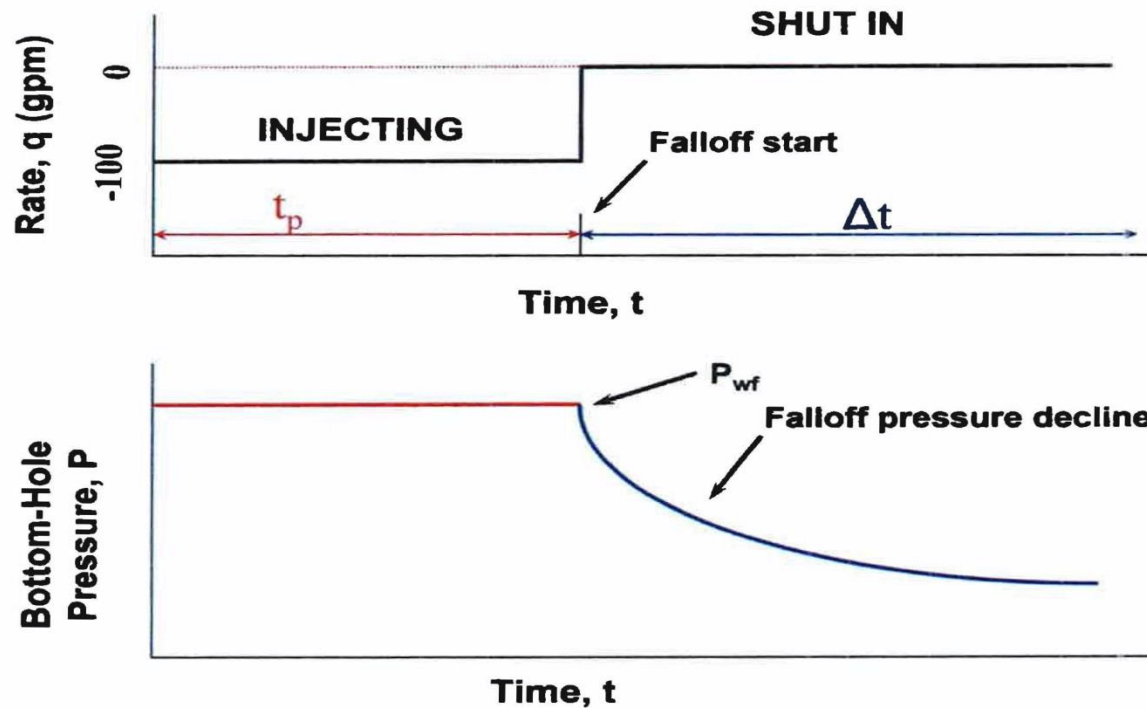
- We shall describe the reservoir’s pressure response to flow during a test by considering the very simplest reservoir model; one with single-phase, radial flow in a homogeneous, isotropic reservoir with an “outer boundary” that may be considered “infinite”, and a constant flow rate at the wellbore (“inner boundary”). All flow occurs radially through a horizontal reservoir between impermeable upper and lower reservoir boundaries. The well fully penetrates the reservoir vertically and is fully perforated (or openhole). The reservoir rock and fluid properties are assumed to be uniform throughout the reservoir and the fluid properties are assumed to be independent of pressure. In reality no reservoir satisfies all of these assumptions; however, we can compare the actual reservoir response with the ideal case for equivalence or divergence. We may refer to this model as the ideal reservoir model and use it to describe the simplest expected pressure response during well testing.

#### References:

- 1. Johnson, K. and Lopez, S., 2003, *The Nuts and Bolts of Falloff Testing*, EPA Region 6
- 2. KDHE, Bureau of Water, Geology Section, 2013, *KDHE Overview of the UIC Program Addressing Class 1 Disposal Wells*



# WHAT IS A PRESSURE FALL-OFF TEST?



# WHY PERFORM A PRESSURE FALL-OFF TEST? (PFO)

- Class I disposal well rules and regulations, beginning in 1989 under the Underground Injection Control (UIC) program, are regulated by KDHE and require annual Pressure Fall-Off tests.
- According to KDHE regulation 28-46-30, which references 40 CFR (Code of Federal Regulations) 146.13 (d) and UIC Permit require monitoring of the pressure build up in the injection zone at least annually, including at a minimum, shut down of the well for a time sufficient to conduct a valid observation of the pressure fall-off.
- Measure reservoir pressures: Reservoir pressure increases associated with long term fluid injection can be estimated. Year to year comparisons of reservoir conditions.
- Obtain reservoir parameters: The testing permits determination of reservoir characteristics including permeability and skin as well as identification of fracturing.
- PFO will let operator know when the disposal zone becomes plugged off, which gives the operator time to develop a plan to remedy the problem.



# KEY TERMS and DEFINITIONS

- **STB/day** = Stock Tank Barrels ( 42 gallons per barrel) per day is the volume of injection fluid injected during the test.
- **Flow Efficiency (F)** = is a mathematical means of expressing the ability of a reservoir to deliver fluid to the wellbore.
- **Skin (s)** = Typically, any unintended impedance to the flow of fluids into or out of a wellbore is referred to as formation damage. This broad definition includes flow restrictions caused by a reduction in permeability in the near-wellbore region.

**Positive Skin** = Indicates the wellbore has damage.

**Negative Skin** = Indicates no wellbore damage

- **Pressure drop due to Skin** = Represents the total pressure drop caused by apparent or total skin.
- **P\*** = Assumption of average reservoir pressure. Formation pressure detected during late time flow regime.
- **Flow Capacity** = Is a measure of how conductive or how easily fluid moves through a formation.

# KEY TERMS and DEFINITIONS

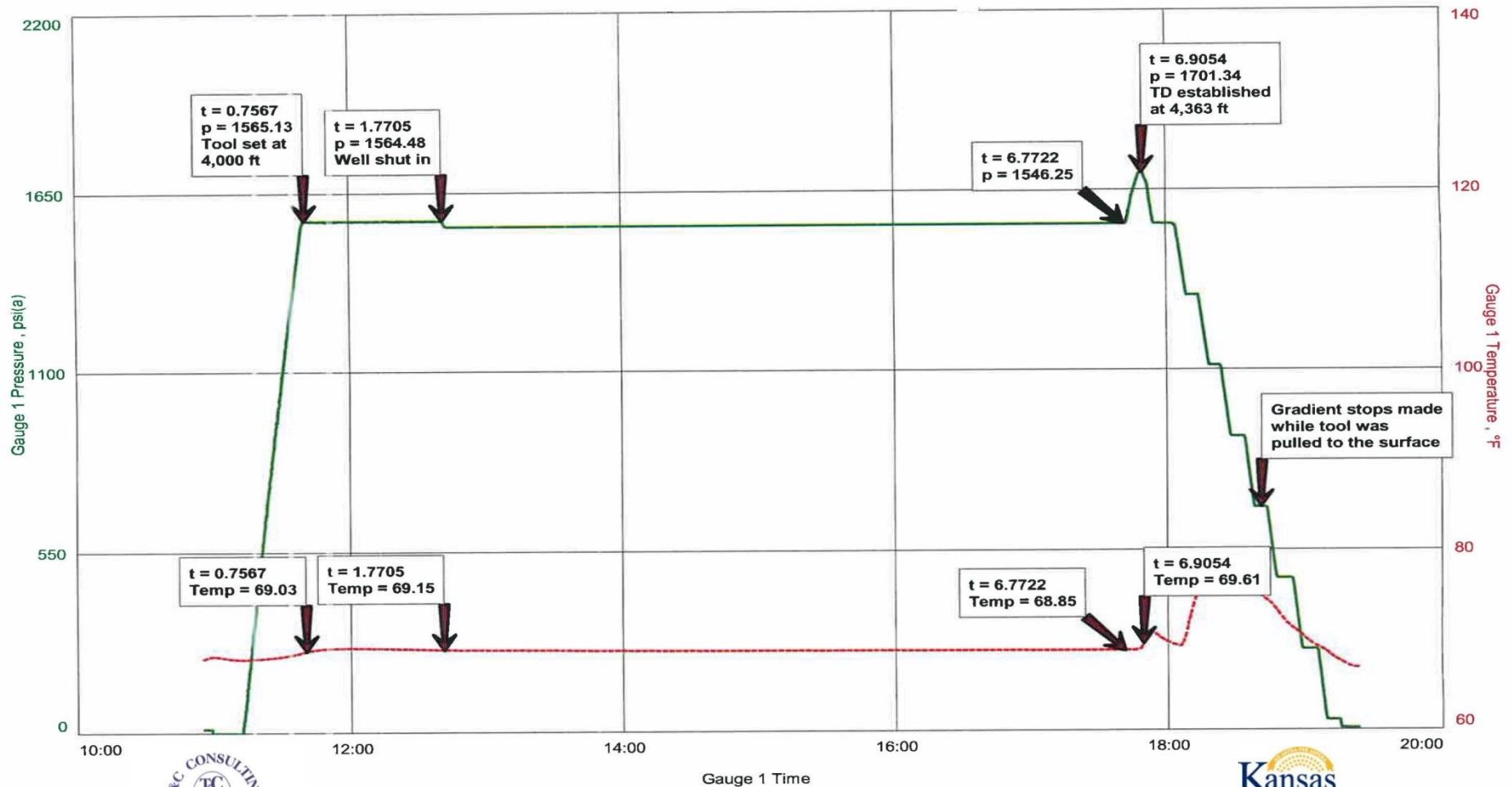
- **Porosity ( $\emptyset$ )**= Is a measure of the void (i.e. empty) spaces in a material, and is a fraction of the void over total volume, between 0 and 100%. Used in geology, hydrogeology, and soil science, the porosity of a porous medium (such as rock or sediment) describes the fraction of void space in the material where the void may contain gas, oil or water.
- **Radius of Investigation** = Represents how far into the reservoir the transient effects have traveled.
- **Static Fluid Level** = The level of the fluid in a well when the well is shut-in. The hydrostatic head of this fluid is equal to the bottom hole pressure.
- **Permeability ( $k$ )** = is the property of rocks that is an indication of the ability for fluids to flow through rocks
- **Transmissivity ( $kh/\mu$ )** = is the rate at which groundwater and/or formation water flows horizontally through an aquifer.

# KEY TERMS and DEFINITIONS

- **q** = flow rate, barrels per day (positive for production, negative for injection)
- **u** = viscosity, cP (centipoise)
- **h** = net pay, ft
- **P** = pressure, psi
- **m** = slope of horner plot, psi/cycle
- **r<sub>inv</sub>** = radius of investigation, ft. (distance a pressure transient has moved into a formation following a rate change in the well)

# PRESSURE & TEMPERATURE DURING the TEST

Waste Water Disposal Well #  
Formation: Arbuckle



# PRESSURE FALL-OFF TESTS

There are basically two phase's for performing a PFO as per T&C Consulting guidelines:

- **PHASE ONE** is the planning, preparation, and field work, which is performed by the operating company personnel, the consulting supervisor, and the wire logging contractor.
- **PHASE TWO** is the analytical portion, whereby the downhole data, collected during Phase One, is analyzed and is presented in a formal report.

# PHASE ONE

- A pressure fall-off plan will be submitted to the (KDHE) for approval. This plan will provide the operator's name, facility location, and well number, permit number, well depth information, depth of disposal interval, and estimated date the test will be performed.
- Prior to the PFO test, a meeting will be scheduled with the Operator to discuss the time to start the flow and provide water sample bottles. Samples of the waste water should be obtained at various times during the flow period.
- Standard procedure for the test will be discussed also.
- The injection rate must be high enough and continuous for a period of time sufficient to produce a pressure buildup that will result in valid test data. Prior to initiating injection, an initial flow meter reading will be recorded.
- The injection rate should be the maximum injection rate that can be feasibly maintained constant in order to maximize pressure changes in the formation and provide valid test results but not exceeding the daily injection volume limit of the UIC permit.
- The logging contractor will move on location and rig up over the well and will then run their wireline pressure/temperature tool to a predetermined depth.
- Once this depth is reached the tool is secured and the flowing bottom hole pressure and temperature is monitored for approximately one hour.

# PHASE ONE

## continued

- After the flowing bottom hole pressure/temperature is monitored and recorded, injection is terminated and the final flow meter reading is recorded. This will commence the fall-off phase of the test.
- The fall-off portion of the test must be conducted for a length of time sufficient such that the pressure is no longer influenced by wellbore storage or skin effects and enough data points lie within the infinite acting period and the semilog straight line is well developed.
- Normally this is achieved within five hours after injection is ceased, but can take longer depending on well conditions.
- At the conclusion of the fall-off test, the logging tool is lowered to establish total depth, which will be compared to previous years depth recordings.
- The logging tool is then pulled at 250 feet to 500 feet intervals, depending on the depth of the well, whereby pressure and temperature readings are recorded at each interval. This data will later determine the static fluid level of the well at the time of the test.

# FALL-OFF TEST PLAN



## CLASS I DISPOSAL WELL FORMATION PRESSURE FALL-OFF TEST PLAN

To: Kansas Department of Health and Environment (KDHE) Bureau of Water – Geology 1000 SW Jackson Street, Suite 420 Topeka, Kansas 66612-1367	For: ***** Facility: ***** Location: <u>Waste Water Disposal Well #*</u>
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The formation pressure fall-off test will be conducted on the following described Class I injection well(s) and the results and interpretation submitted in accordance with the KDHE procedure document titled **“Formation Pressure Fall-Off Test and Testing Plan Development Procedures – Procedure #UICI-2”** found at <http://kdheks.gov/uic/download/UICI-2.pdf>.

Well Data: (BGL = Below Ground Level)

Well ID #/KDHE Permit #	Approximate Depth of Pressure Tool	Injection Interval BGL	Casing Seat Feet BGL
KS-**-***-***	4,000 feet	3,938 ft. to 4,225 ft.	3,938 ft.
	(See Attachment A)	(See Attachment A)	(See Attachment A)

Describe the injection liquid to be used for the test: Facility Waste Water

Describe the location where the well will be shut-in for the shut-in part of the test: The flow line control valve is approximately eight feet from the disposal tubing (See Attachment B).

**If the stabilization injection period is interrupted for any reason and for any length of time, the stabilization injection period must be restarted.**

**Any test not shut-in for a sufficient time to develop an infinite acting radial flow period during the fall-off portion of the test shall be rerun using a procedure that will result in valid test results.**

The formation pressure fall-off test is schedule to be conducted on: \*\*\*\*, \*\* 2015 (date)

  
Signature

Field Consulting Technician  
Title

T&C Consulting  
Company

\*/\*\*/15  
Date

Facility contact information for this formation pressure fall-off test plan:

\*\*\*\*\*  
E-mail

\*\*\*\*\*  
Telephone Number

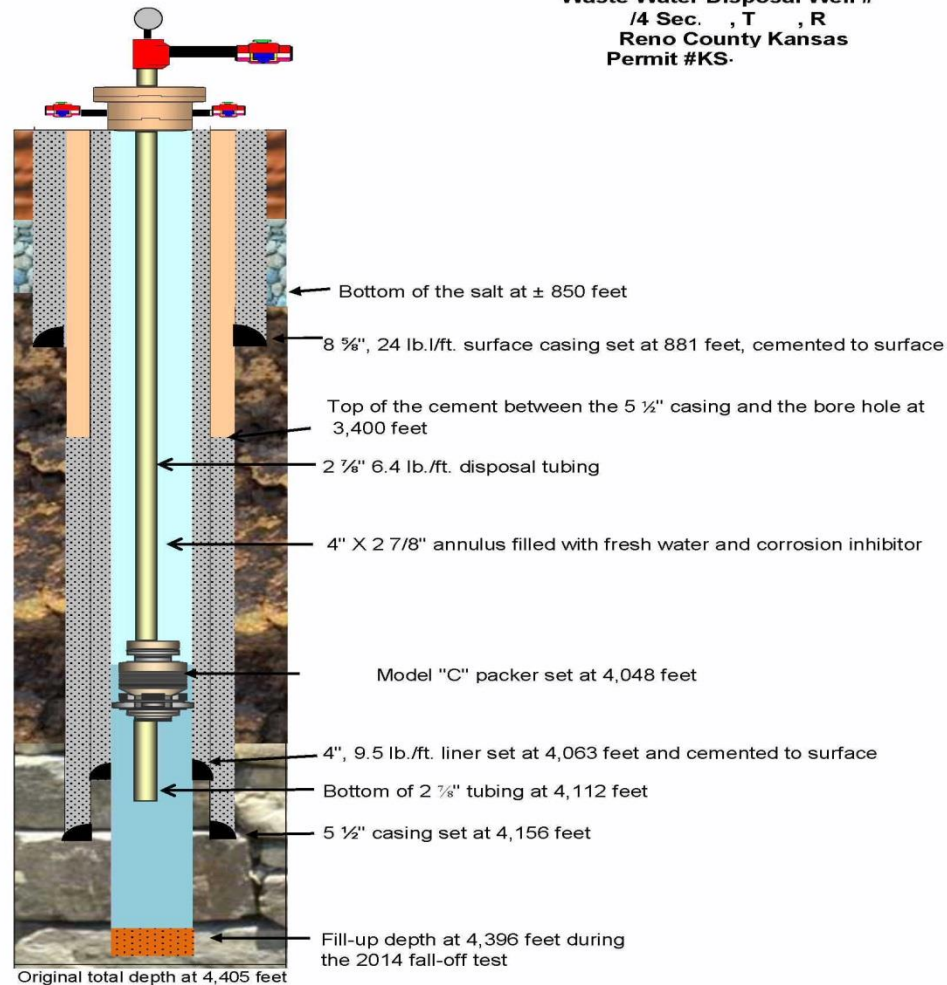
Db  
c/uic forms/Class I Disposal Well Formation Pressure Fall-Off Test Plan  
04/11/2011





# PFO TEST PLAN/WELL DIAGRAM

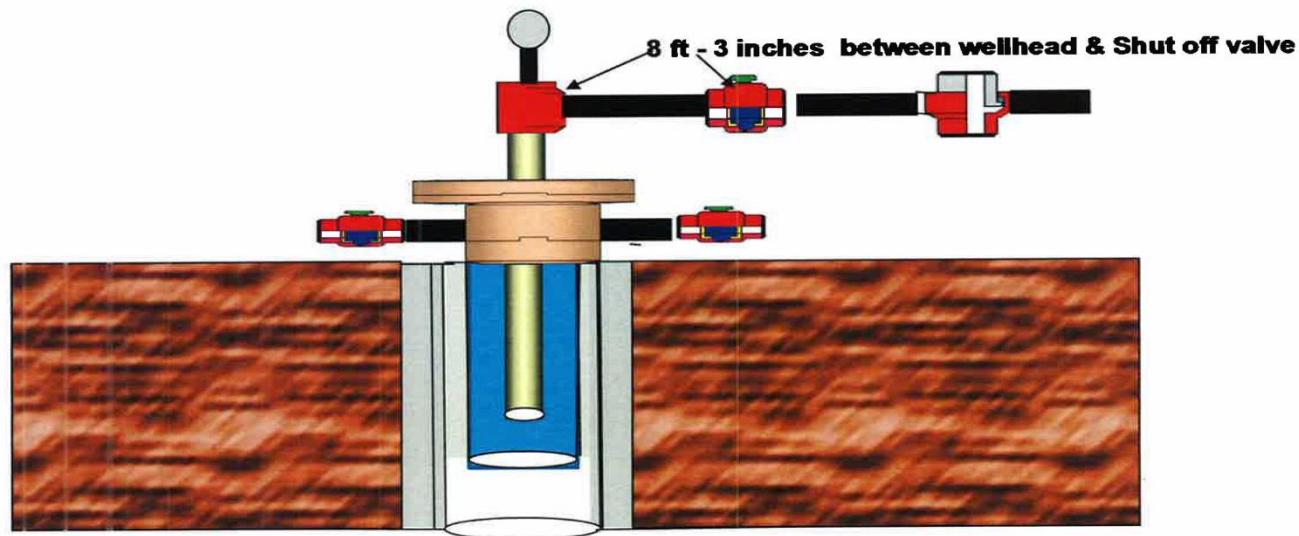
, Kansas Facility  
Waste Water Disposal Well #  
/4 Sec. , T , R  
Reno County Kansas  
Permit #KS.



# PFO TEST PLAN

continued

\*\*\*\*\* \*\*\*\*\* Storage Facility  
Waste Water Disposal Well #\*  
\*\*/4 Sec. \*\*, T\*\*, R\*\*  
\*\*\*\*\* County, Kansas  
Permit # KS-\*\*-\*\*\*-\*\*\*



# PFO TOOL





# VIEW OF DISPOSAL WELL PRIOR TO SPOTTING IN AND STARTING TEST



# LOGGING TRUCK SERVICE UNIT







# LUBRICATOR ON TOP OF WELLHEAD

# LOGGING TRUCK





# CONTROL PANEL INSIDE OF TRUCK



# PHASE TWO

- With the conclusion of Phase One, all field notes (flow times, flow meter readings), water samples, and bottom hole pressure and temperature data recorded during the test will be analyzed for the final test report.
- As per KDHE's fall-off test procedures, the final report must provide the following information and evaluations:
  1. A log-log plot with a derivative diagnostic plot used to identify flow regimes. The wellbore storage portion and infinite action portion of the test must be identified on the plot. Type curves must be used to verify results.
  2. A Horner plot must be used to calculate the  $kh/\mu$  product and to determine  $P^*$ . An expanded Horner plot containing the entire infinite acting portion must be reproduced in order to permit a close inspection of the semilog slope and any data fluctuations. The slope used to calculate the  $kh/\mu$  product and to determine  $P^*$  must be drawn on both Horner plots. In addition, the wellbore storage portion and infinite acting portion of the test must be identified on both plots.

# PHASE TWO

continued

3. The “h” value (injection interval thickness) used must be agreed upon between KDHE and the permittee. For formations with characteristics such as the Arbuckle Formation, the injection interval should be considered the entire thickness of the injection formation in the area.
4. The viscosity used in analyzing the test must be that of the liquid through which the pressure transient was propagating during the infinite acting portion of the test. The information used to determine the viscosity must be provided.
5. Any test that was not shut-in long enough to develop an infinite acting period, or cannot be properly analyzed for the  $kh/\mu$  group of parameters using the Horner method, should be rerun, using a procedure that will result in valid test results, unless other arrangements have been made with KDHE.
6. All equations used in the analysis must be provided with the appropriate parameters substituted in them.

# PHASE TWO

## continued

7. Tests conducted in relatively transmissive reservoirs are more sensitive to the temperature compensation mechanism of the gauge, because the pressure buildup response evaluated is smaller. For this reason, the plot of the temperature data should be reviewed. Any temperature anomalies should be noted to determine if they correspond to pressure anomalies.
8. Explain any anomalous data responses. The analyst should investigate physical causes other than reservoir responses.

The report must contain: facility name, location, well number, KDHE permit number, a well schematic depicting current completion and location of the pressure measuring tool during the test, the wellbore radius, completed interval and type of completion, distance between offset wells completed in the same injection interval, and status of each offset well and any impact they had on the rest, daily job log of testing activities, a description of the downhole pressure gauge used, including the manufacturer, type, resolution, calibration certificate and date of recalibration, time of injection period, type of injection liquid, final injection pressure and temperature, total shut-in time, final static pressure and temperature.

Additionally, the report must contain values for permeability, transmissibility, Skin (s), Pressure drop due to skin, Slope of slopes determined from the Horner plot, Radius of investigation, Time to beginning of the infinite acting portion of the test (Radial Flow), Flow efficiency, Flow capacity and Pressure at one hour.

# PRESSURE FALL-OFF TEST DATA

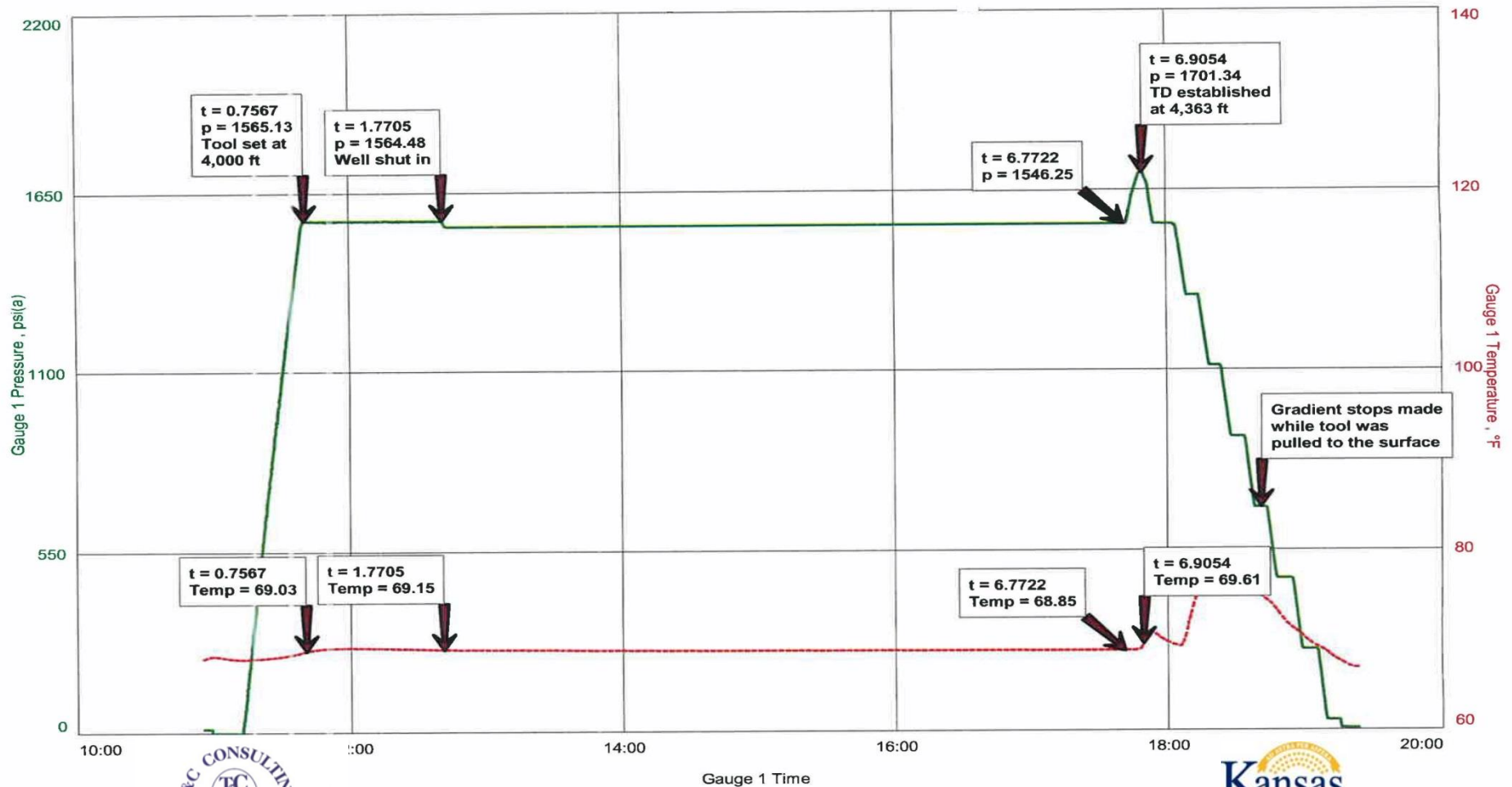
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Page 1

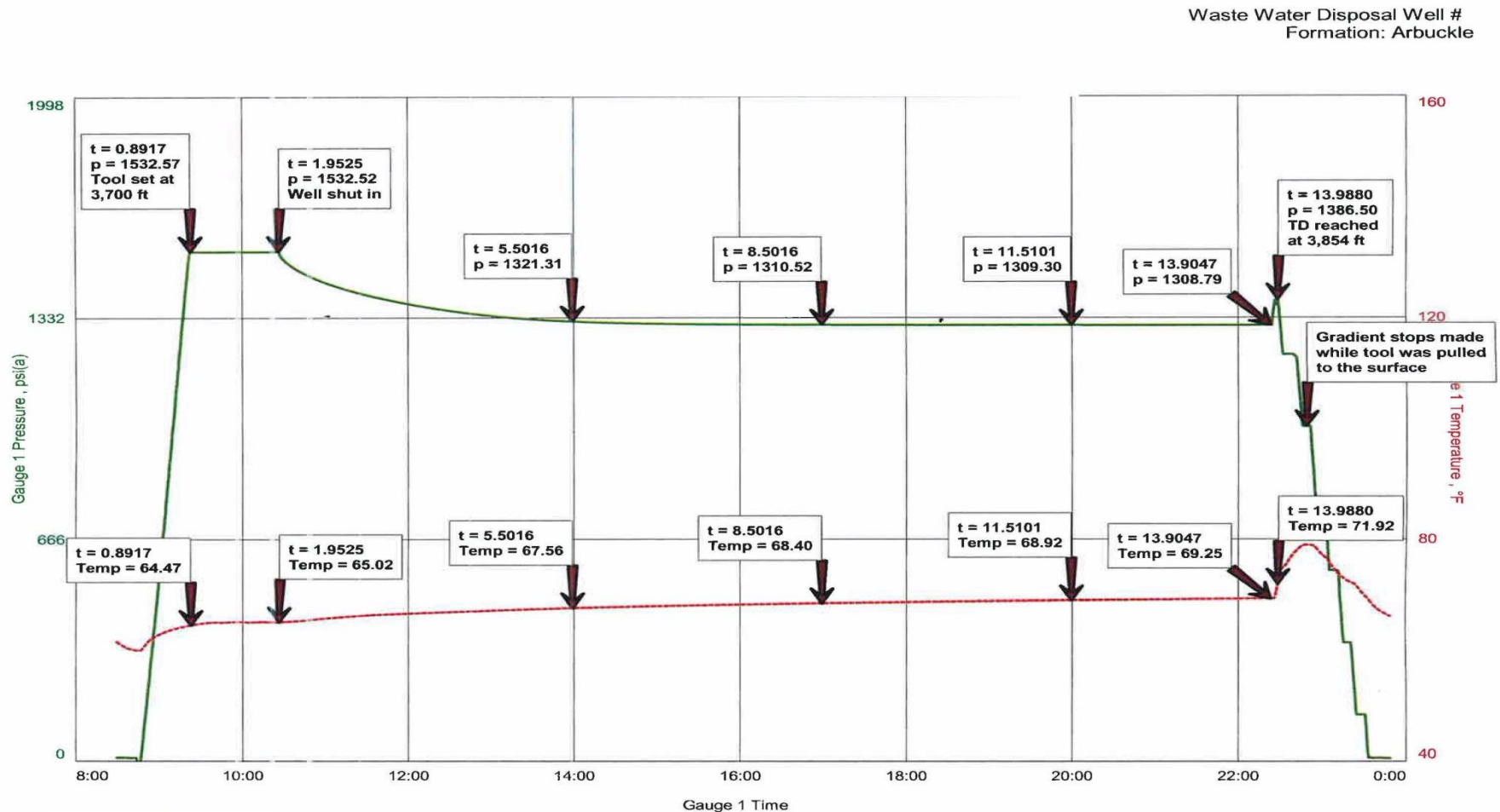
This particular test contained 36 pages of PFO test data

# PRESSURE & TEMPERATURE DURING the TEST

Waste Water Disposal Well #  
Formation: Arbuckle



# PRESSURE & TEMPERATURE vs TIME

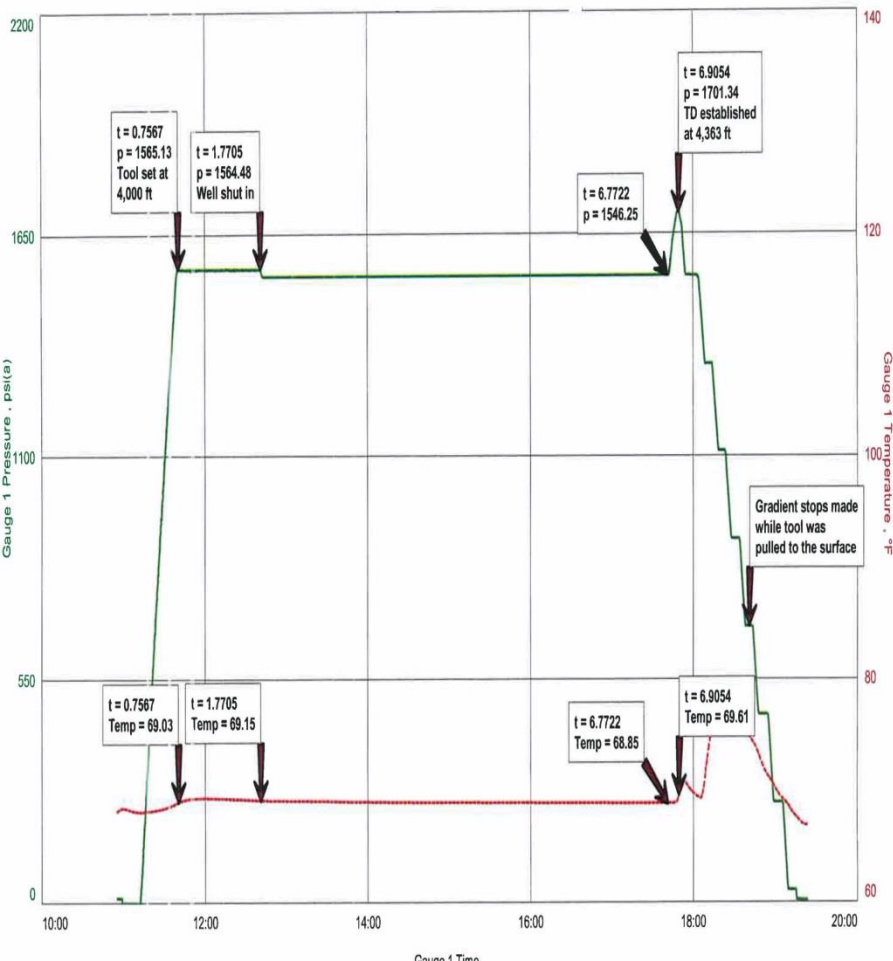




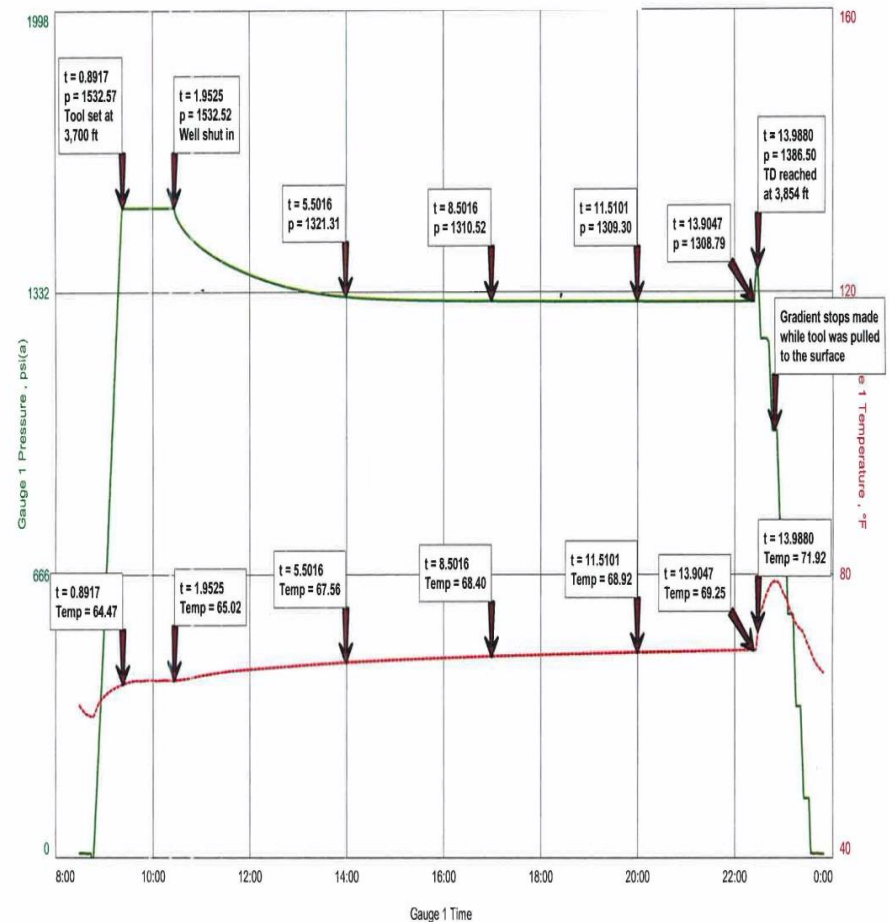
# PRESSURE & TEMPERATURE COMPARISON



Waste Water Disposal Well #  
Formation: Arbuckle



Waste Water Disposal Well #  
Formation: Arbuckle



# SOLUTION TO THE PARTIAL DIFFERENTIAL EQUATION (PDE)

- The exact solution to the PDE is in terms of cumbersome Bessel functions
- Fortunately, an approximate solution based on the exponential integral (Ei) gives almost identical results:

$$P = P_i + 70.6 \frac{q \cdot B \cdot \mu}{k \cdot h} \cdot Ei \left( \frac{-948 \cdot \phi \cdot \mu \cdot c_t \cdot r_w^2}{k \cdot t} \right)$$

**where:**

$$Ei(-x) = - \int_x^{\infty} \frac{e^{-u}}{u} du$$



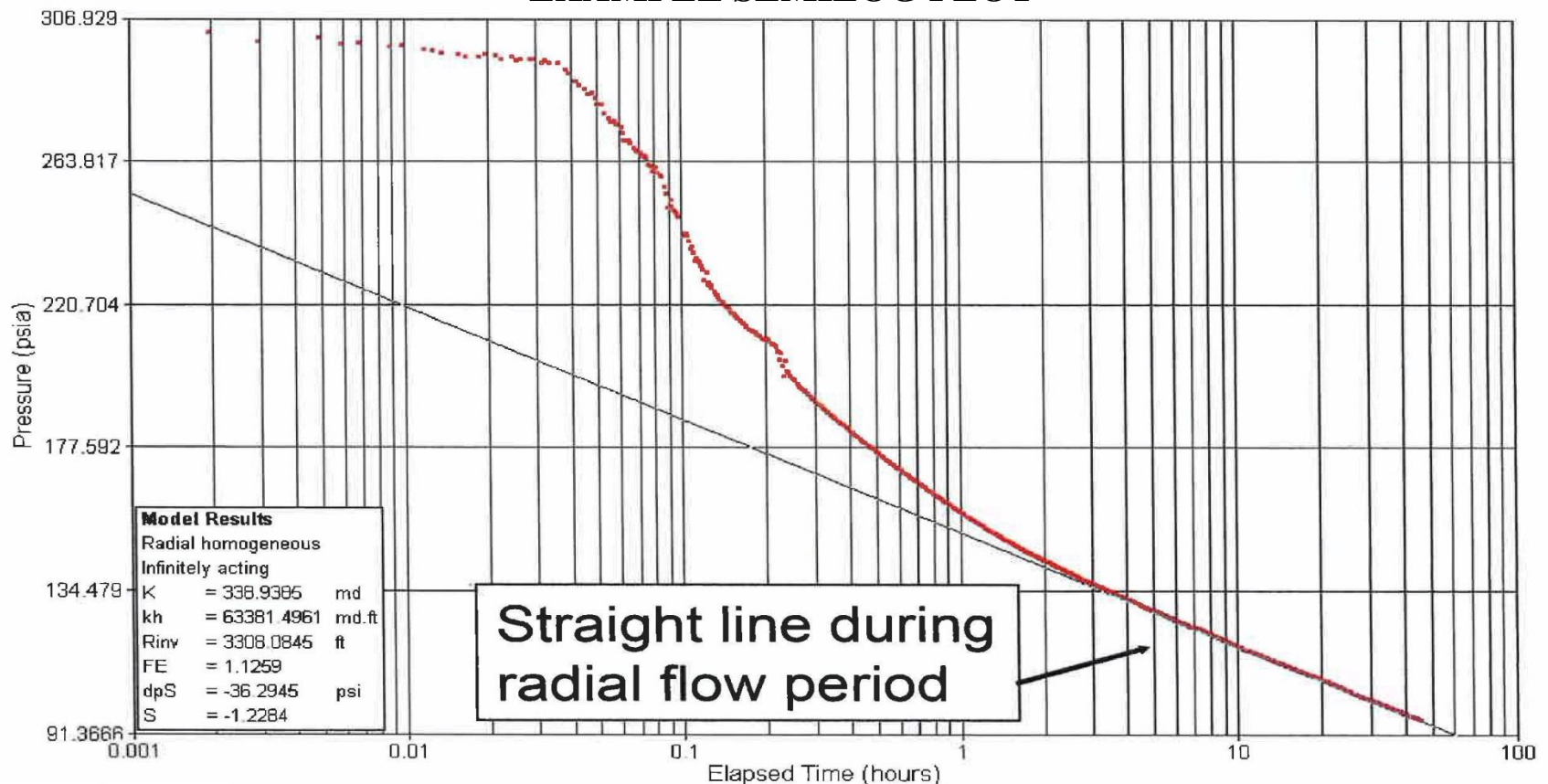
# WELLBORE STORAGE

- Occurs during the early portion of the test
- Caused by shut-in of the well being located at the surface rather than at the sandface
  - ❖ After flow – fluid continues to fall down the well after well is shut-in
  - ❖ Location of shut-in valve away from the well prolongs wellbore storage
- Pressure responses are governed by wellbore conditions not the reservoir
- High wellbore skin or low permeability reservoir may prolong the duration of the wellbore storage period
- A wellbore storage dominated test is unanalyzable

# SEMILOG PLOT USAGE SUMMARY

- A semilog plot is used to evaluate the radial flow portion of the well test
- Reservoir **transmissibility** and **skin factor** are obtained from the slope of the semilog straight line during radial flow

**EXAMPLE SEMILOG PLOT**



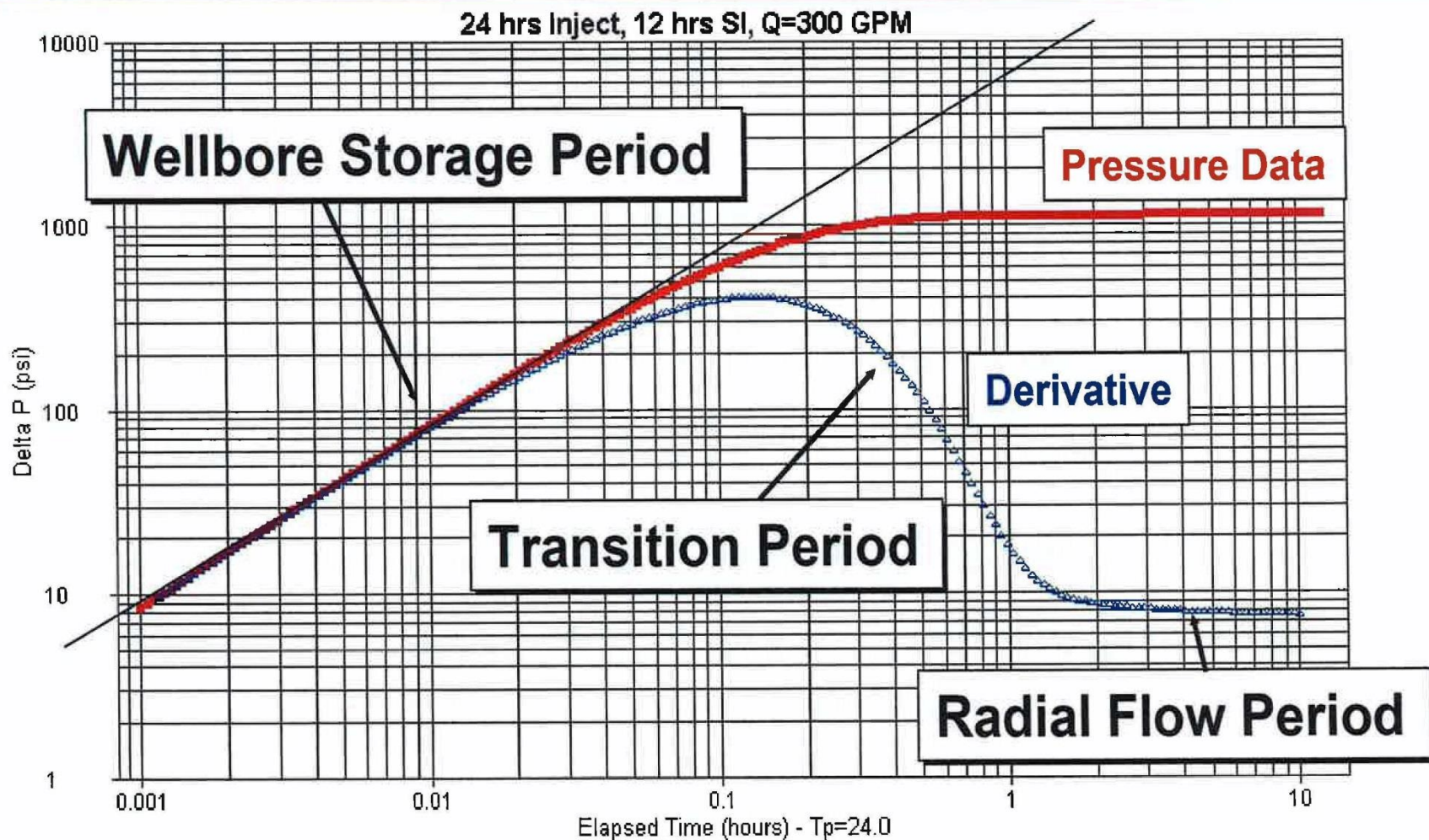
# RADIAL FLOW

- The critical flow regime from which all analysis calculations are performed
- Used to derive key reservoir parameters and completion conditions
- Radial flow characterized by a straight line on the semilog plot
- Characterized by a flattening of the derivative curve on log-log plot

## IDENTIFYING FLOW REGIMES

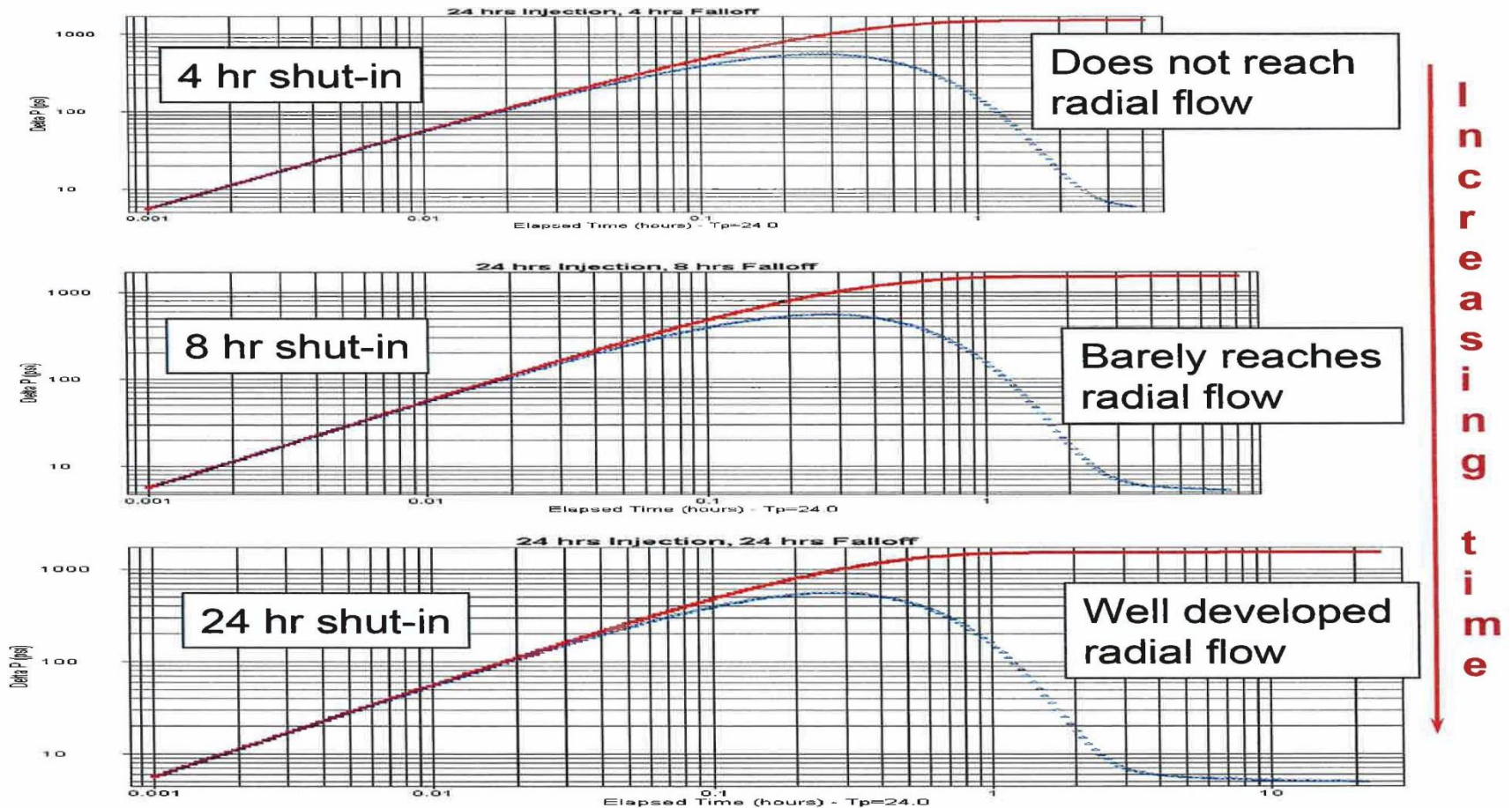
- Create a master **diagnostic** plot, the **Log-log** plot
- Log-log plot contains two curves
- Individual flow regimes:
  - ❖ Characteristic shape
  - ❖ Sequential order
  - ❖ Specific separation
- Critical flow regime – **radial flow**

# LOG-log PLOT

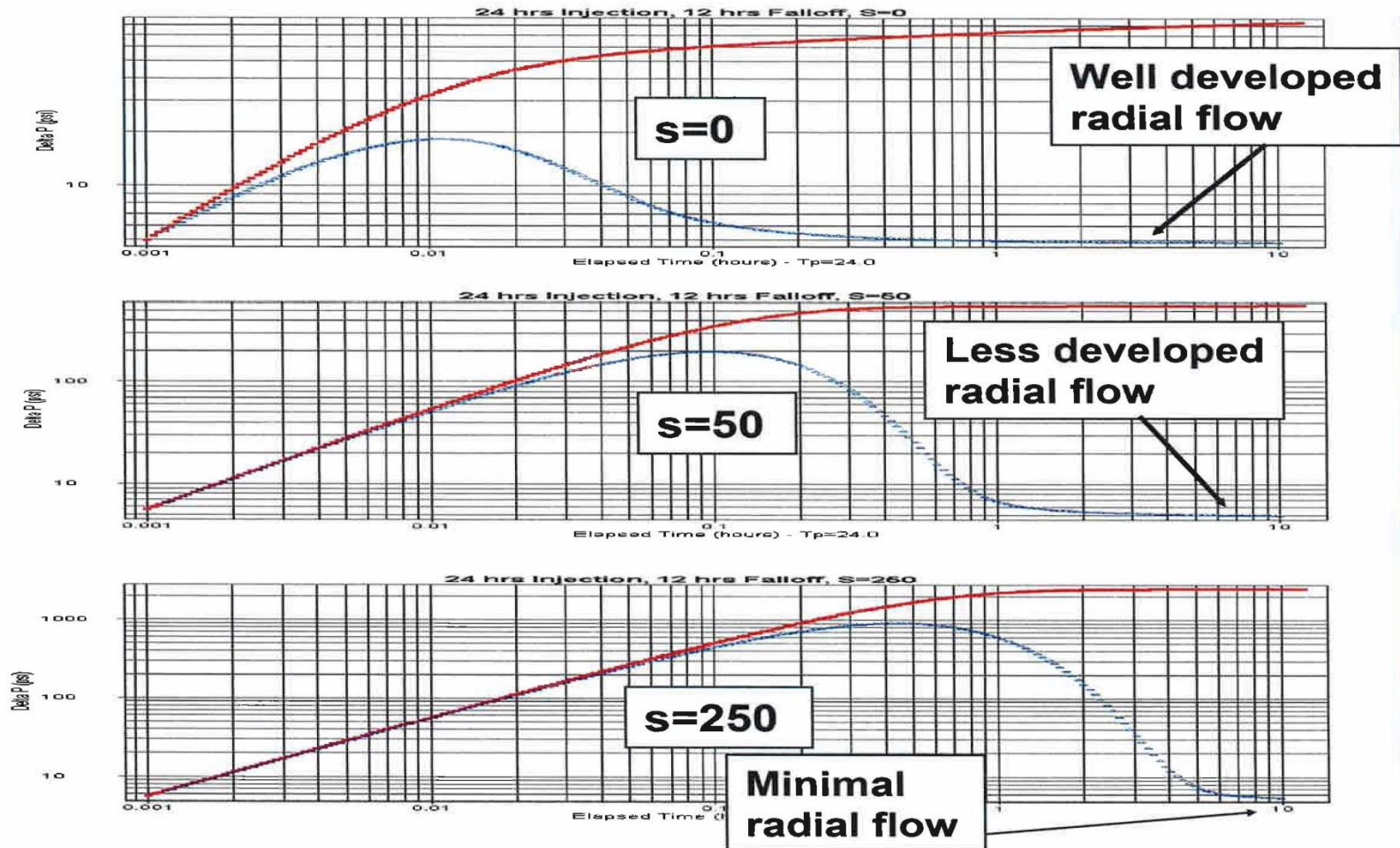




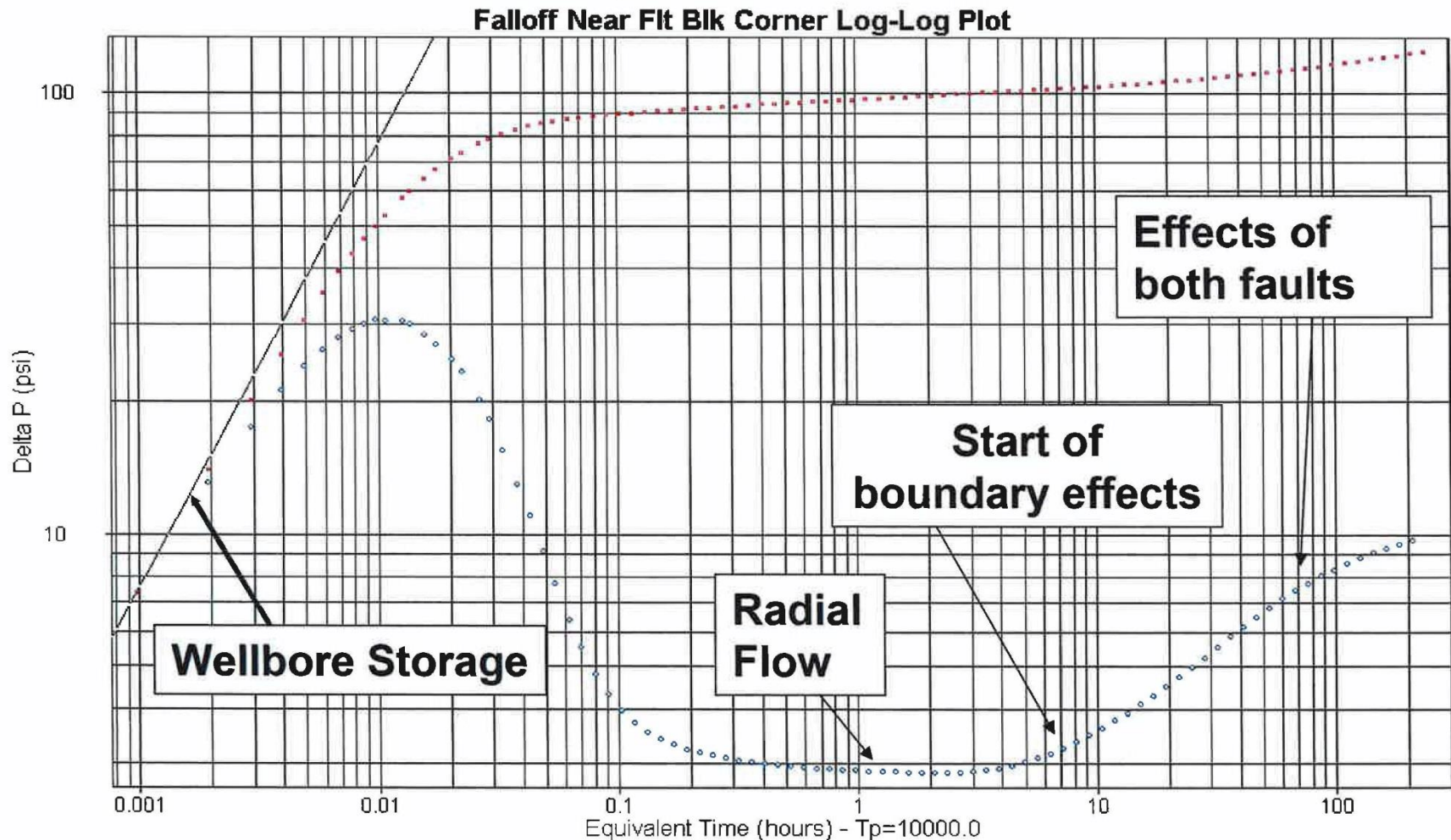
# COMPARISON of SHUT-IN TIMES for IDENTICAL INJECTION CONDITIONS



# COMPARISON of SKIN EFFECT for IDENTICAL FALL-OFF CONDITIONS

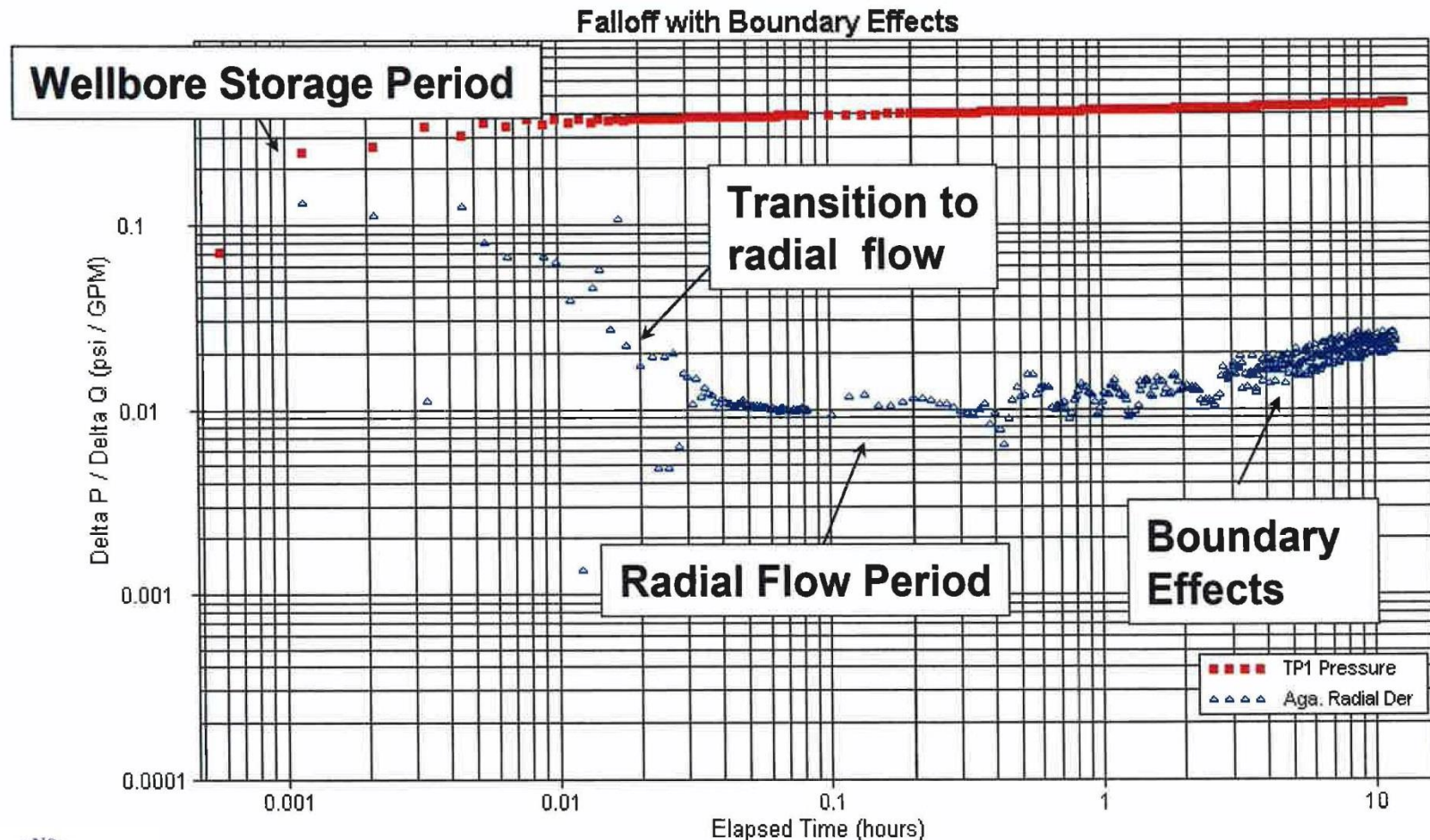


# WHAT DOES the FALL-OFF LOOK LIKE with BOUNDARY EFFECTS?



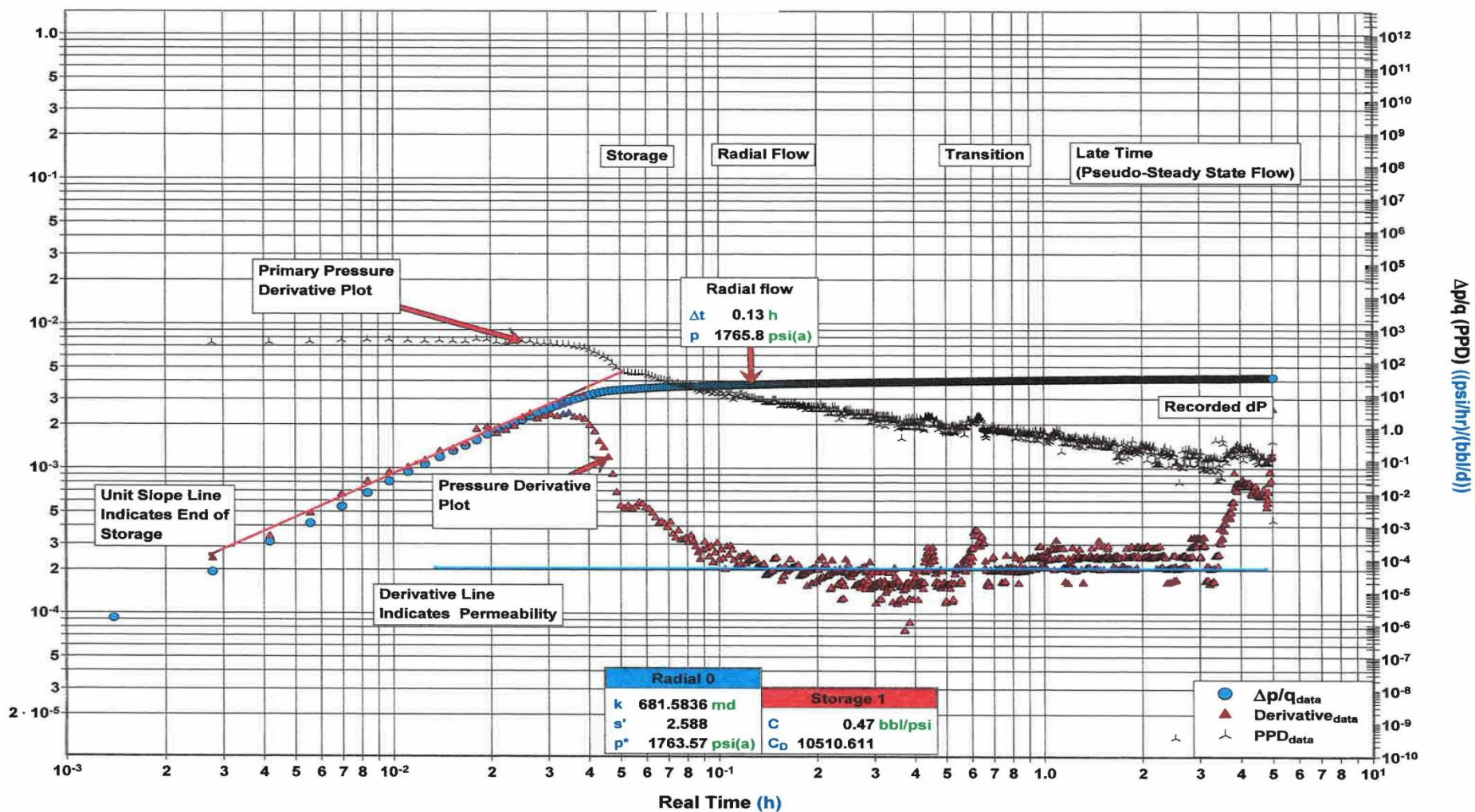


# RADIAL FLOW FOLLOWED by BOUNDARY EFFECTS



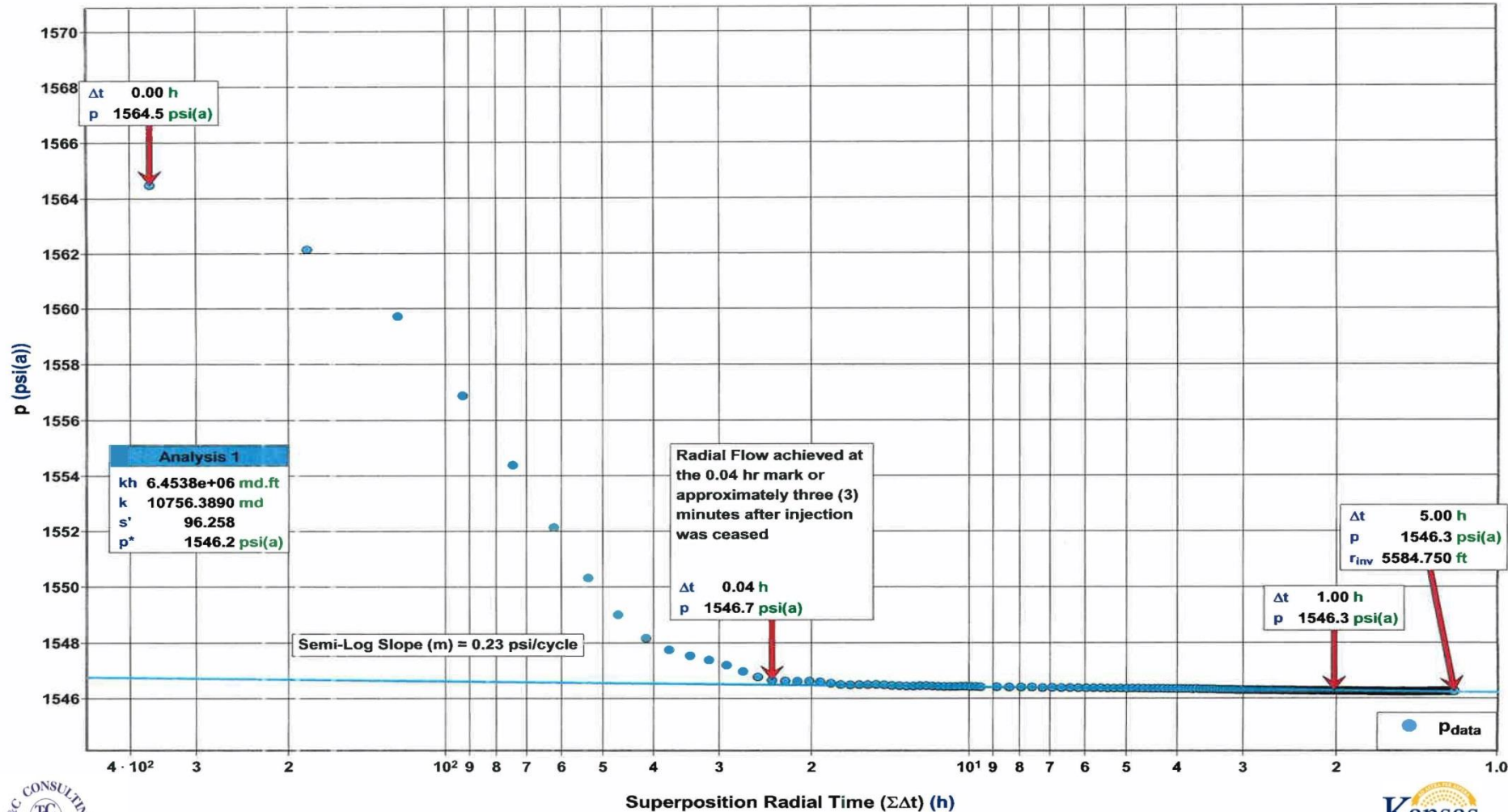


# LOG-log PLOT



**(Pressure & Time)**

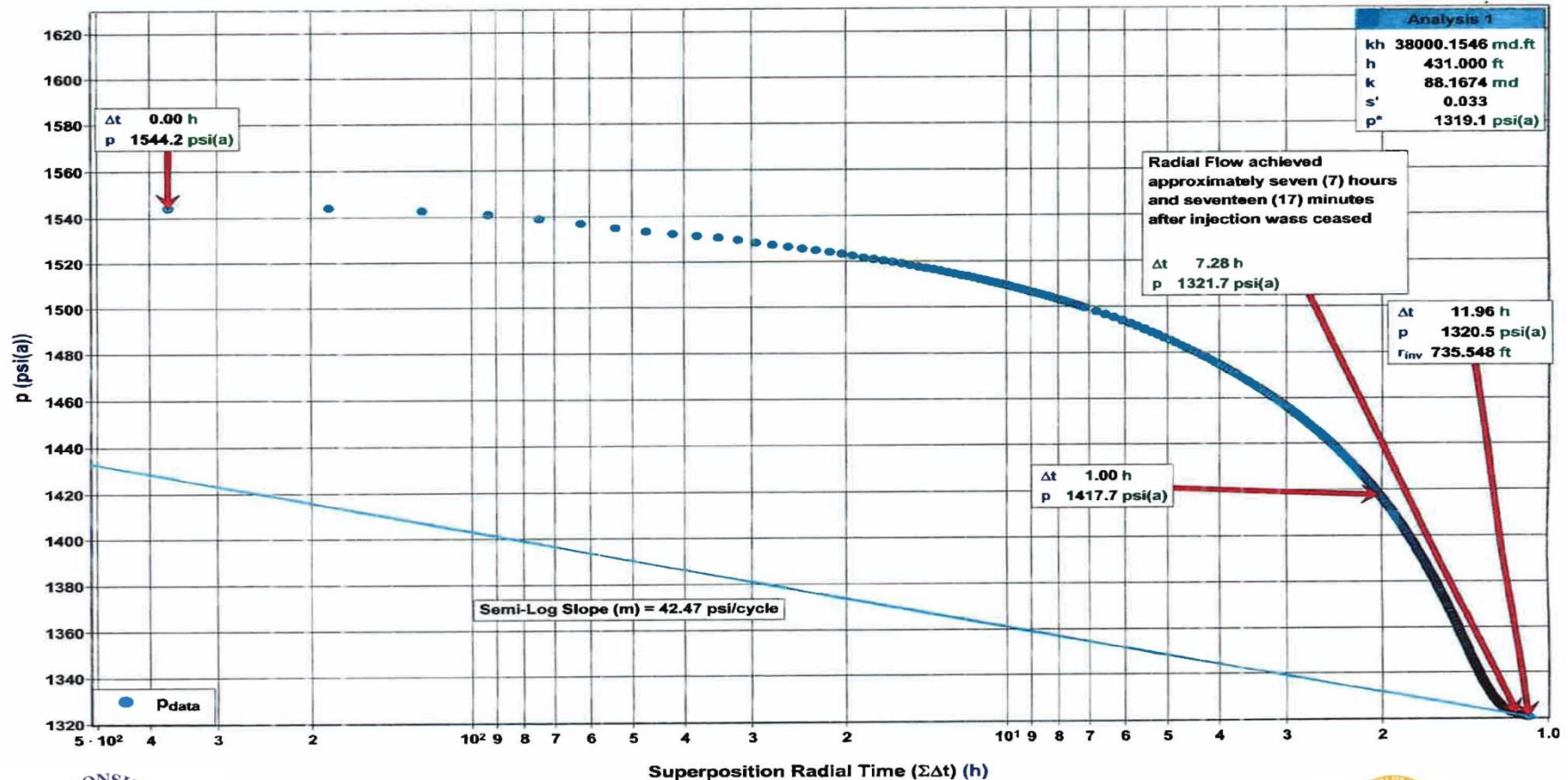
**Waste Water Disposal Well #**  
**Formation: Arbuckle**



# HORNER PLOT

Horner Plot (Presssure & Time)

Waste Water Disposal Well #  
Formation: Arbuckle



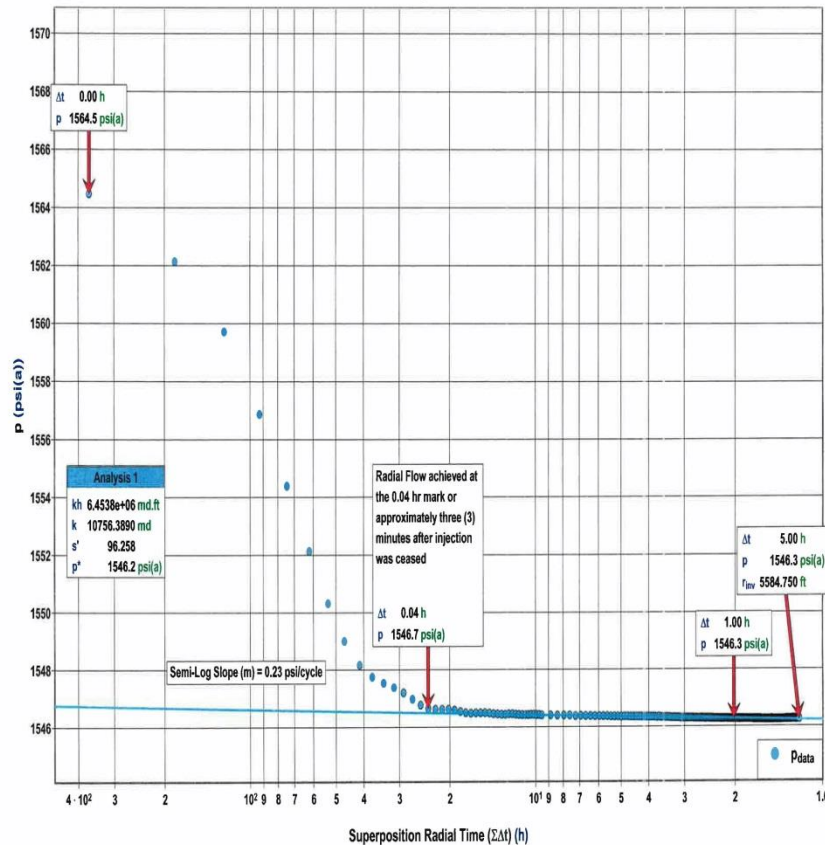


# HORNER PLOT COMPARISONS

Horner Plot (Pressure & Time)

Figure #4

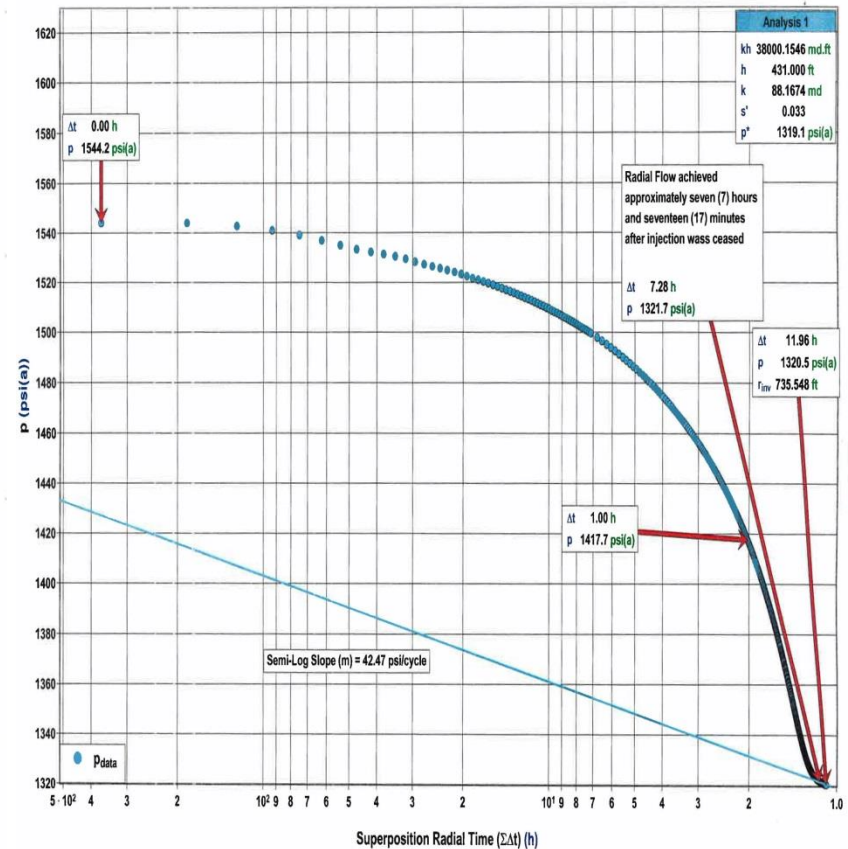
Waste Water Disposal Well #  
Formation: Arbuckle



Horner Plot (Pressure & Time)

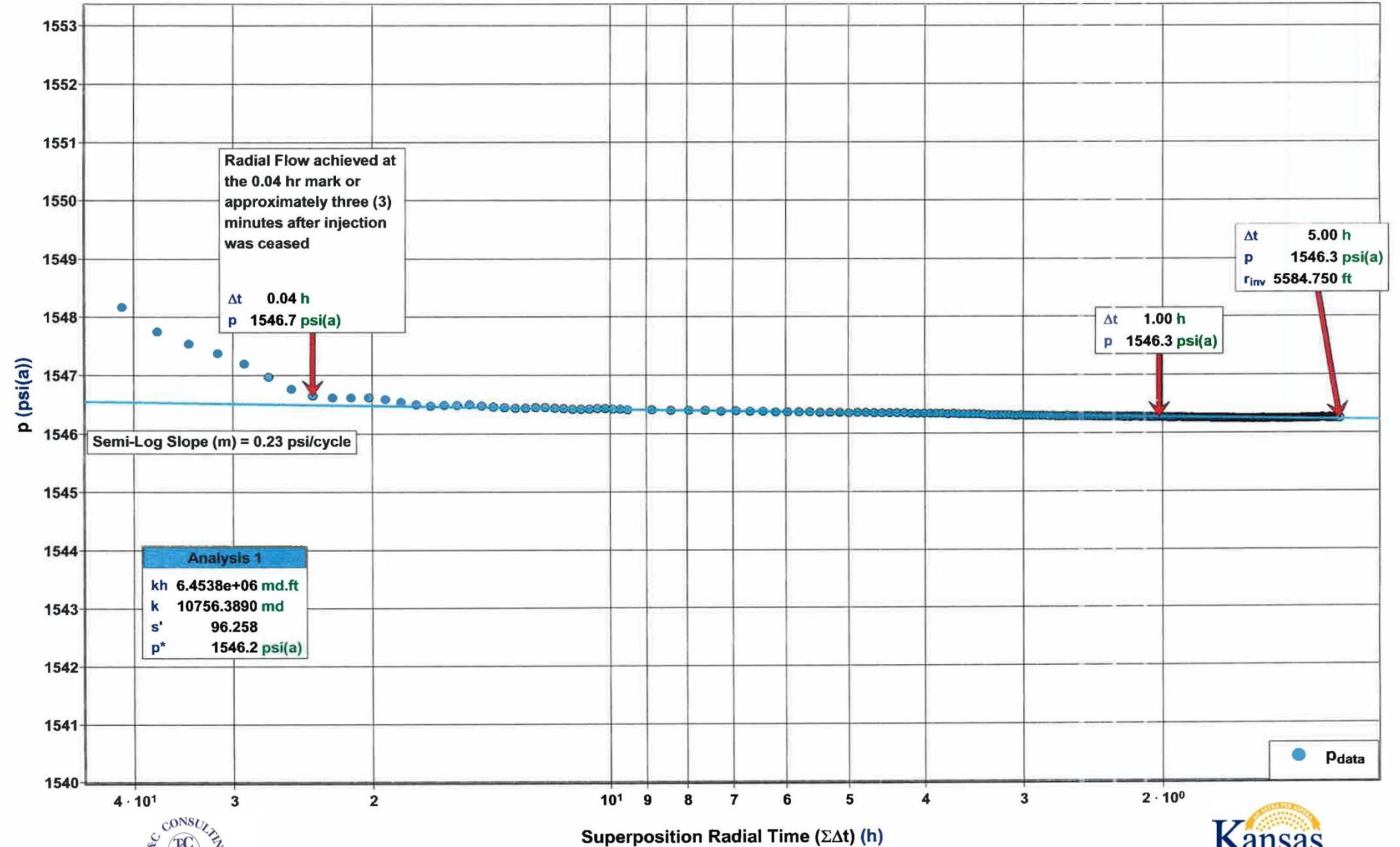
Figure #4

Waste Water Disposal Well #  
Formation: Arbuckle



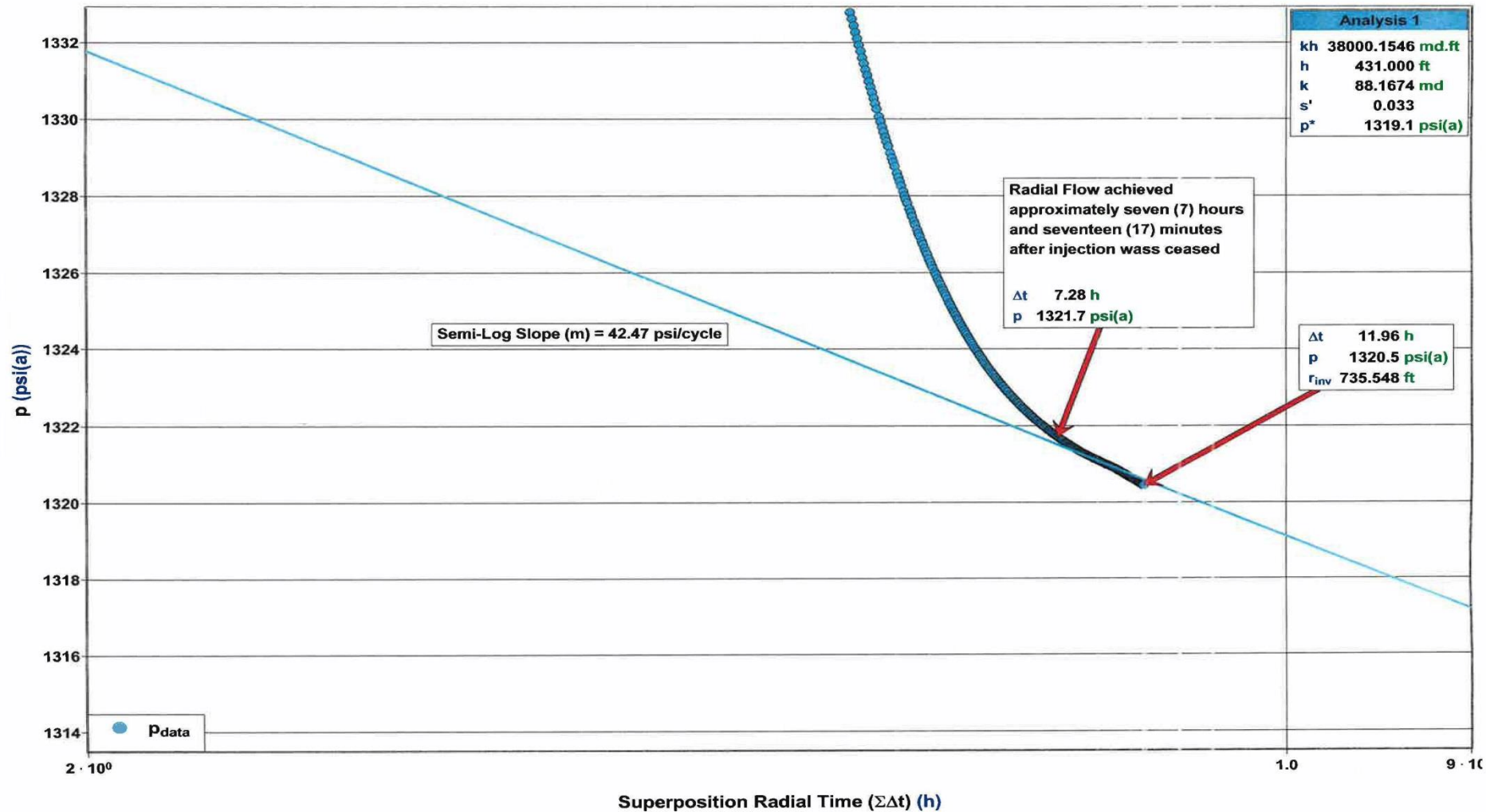
# HORNER PLOT (Pressure & Time) EXPANDED

Waste Water Disposal Well #:  
Formation: Arbuckle

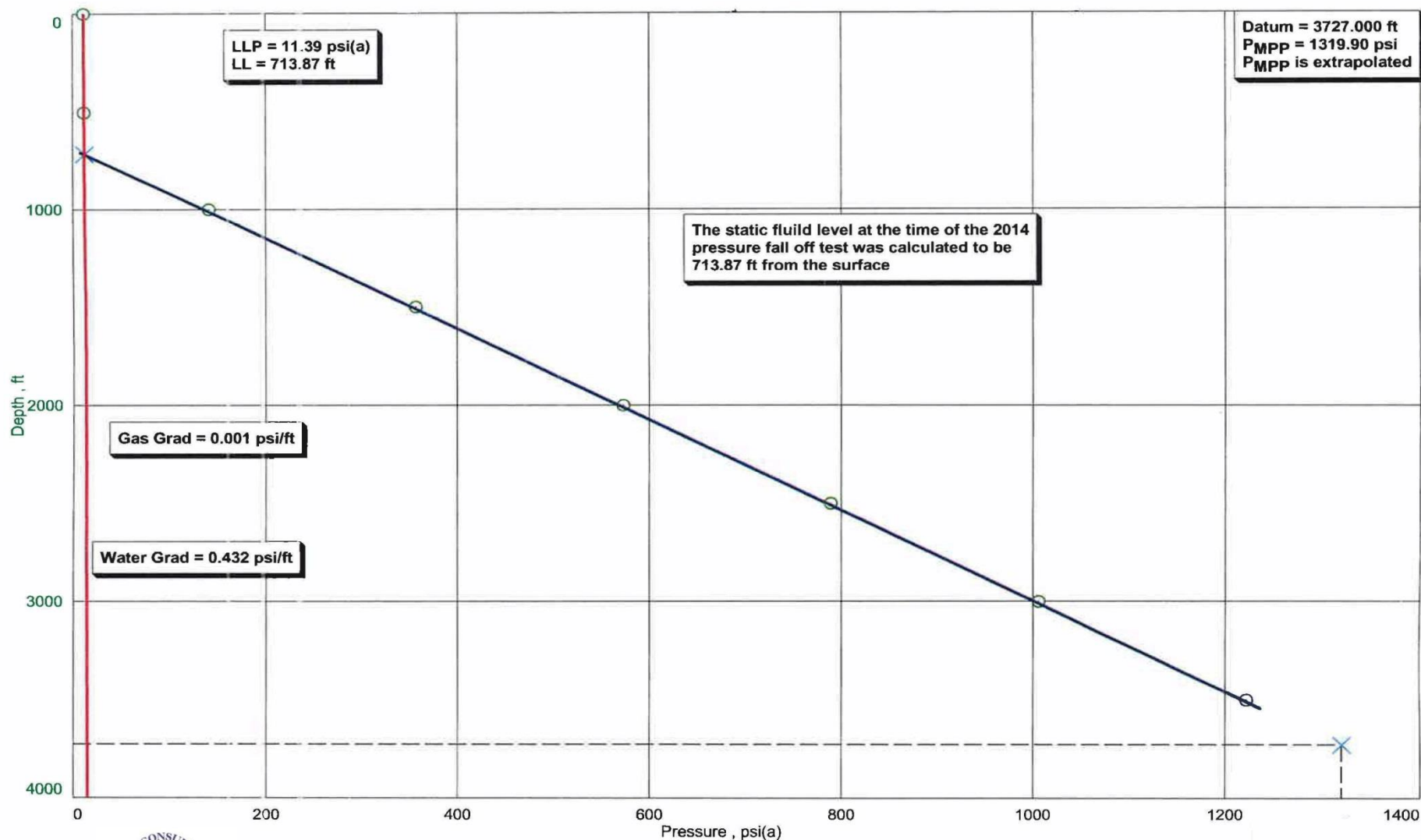


# HORNER PLOT (Pressure & Time) EXPANDED

Waste Water Disposal Well #  
Formation: Arbuckle

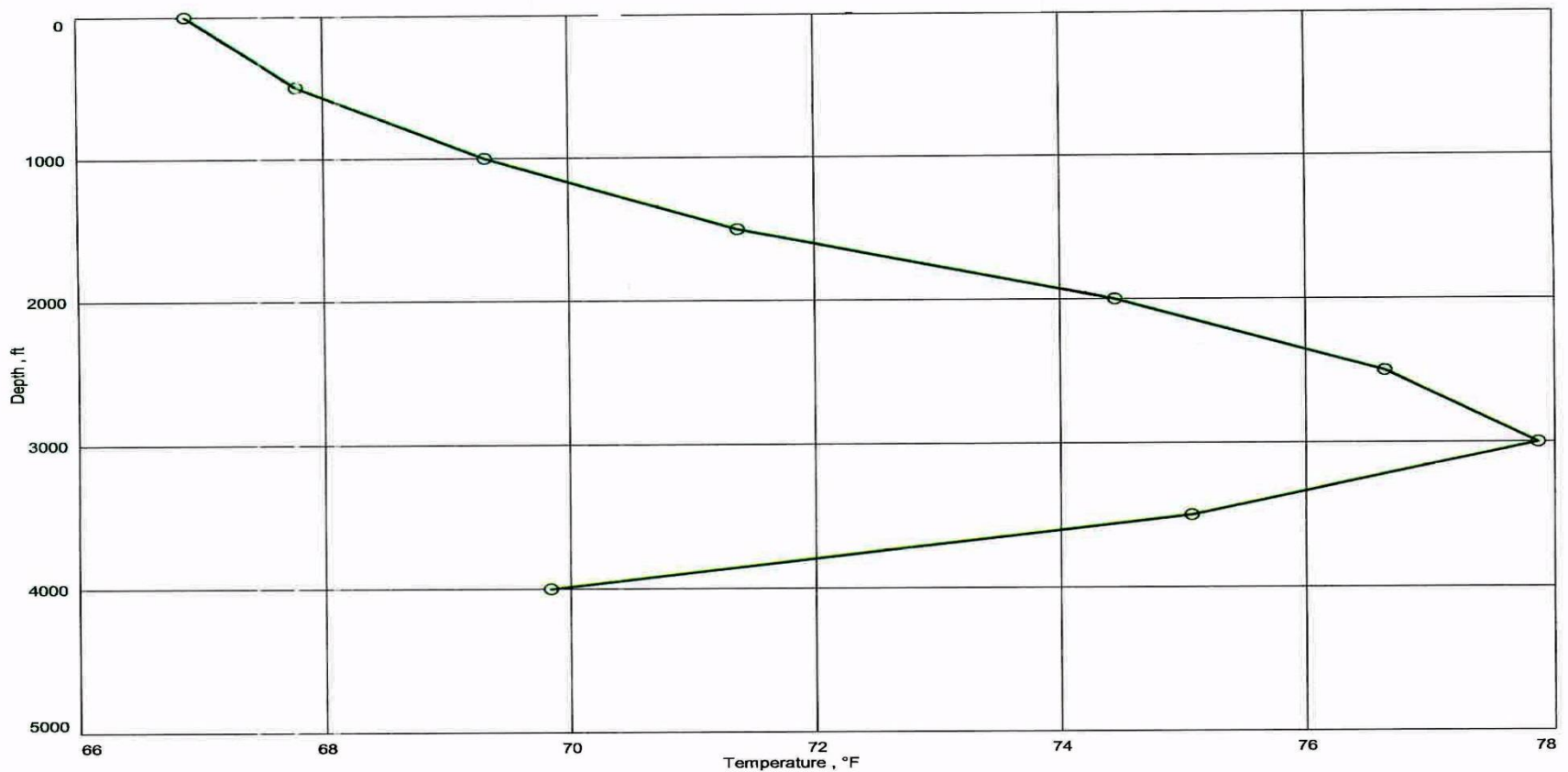


# DEPTH vs PRESSURE (STATIC FLUID LEVEL)



# DEPTH vs TEMPERATURE

Waste Water Disposal Well #  
Formation: Arbuckle







QUESTIONS????????





# **T&C CONSULTING**

**(A DIVISION OF T&C MFG & OPERATING, INC)**

**Would like to  
“THANK YOU”  
for taking time to attend this presentation**

**For additional information, please contact:**

**Dan Murta [620-792-9979](tel:620-792-9979)/[danmurta@tcmfg.com](mailto:danmurta@tcmfg.com)**

**Wayne Jenkinson [620-617-5257](tel:620-617-5257)/[waynej@tcmfg.com](mailto:waynej@tcmfg.com)**

**Craig Pangburn [620-793-2277](tel:620-793-2277)/[craigp@tcmfg.com](mailto:craigp@tcmfg.com)**

